Spatial organization of hydrological processes in small catchments derived from advanced SAR image processing - Field work and preliminary results

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Abstract.

The presented research focusses on the use of active microwave observations to retrieve hydrologically relevant information of surface characteristics (i.e. soil moisture and surface roughness) in river catchments. Given the availability of pairs of SAR data from the tandem mission the following research issues are addressed: (1) development and testing of improved retrieval algorithms for surface characteristics based on the combined use of phase and magnitude information of the return signal from active microwave sensors; (2) use of high resolution field collected data and remotely sensed data to test and validate theories for the catchment scale estimation of soil moisture integrated over soil depth. In particular questions to be investigated include: (2a) what spatial resolution is required for estimation of spatial average soil moisture patterns over a range of scales; (2b) what temporal resolution is required for accurate estimation of the time series of soil moisture.; (2c) what spatial and temporal resolution of data is required to obtain information about the dynamics of soil moisture redistribution within the soil profile using distributed hydrological modelling; (3) study of the influence that spatial organization of soil moisture and vegetation on SAR-based soil moisture retrieval, and of the ability to identify such organization using ERS data; In this respect it will be interesting to study the possibility to use SAR derived digital terrain models for hydrological purposes. In order to accomplish these objectives extensive field campaigns is organized in two small experimental catchments (Tarrawarra near Melbourne, Australia and Wijlegemse beek near Ghent, Belgium). For both catchments a number of ERS-1/2 tandem scenes have been collected. Both Single Look Complex (SLC) and Precision Image (PRI) data will be required to carry out the different steps in the proposed project.

1. Introduction

Since the launch of ERS-1 in 1991 a number of investigations to use SAR PRI data for the retrieval of land surface characteristics useful in hydrologic studies have been reported. Initially, these studies used an empirical approach to relate the back- scattering coefficient to, for instance, moisture content of the upper 5 cm soil layer under different land use. Later, the conversion of the backscattering coefficient to volumetric soil moisture content was based on theoretical surface scattering models (Fung et al., 1994; Altese et al., 1996). All these studies demonstrated the potential of the use of SAR data for spatial and temporal mapping of soil moisture at field scale and over larger areas. However, these studies identified also some of the critical problems related to the accurate retrieval of surface soil moisture from PRI data. Basically, these technical problems are related with the (lack of) detailed knowledge of the surface roughness characteristics. Recently, based on data from an airborne remote sensing campaign (EMAC'94), Su et al. (1996) developed a method to retrieve both soil moisture and surface roughness (expressed in terms of the roughness slope, i.e. the ratio between the root mean square height difference and the correlation length) using two successive SAR scenes in different frequencies. They also demonstrate that accurate soil moisture retrieval at the field scale is possible through the use of this so-called effective roughness slope.

The availabillity of the ERS-1/2 tandem offers the possibility to test another approach to improve SAR-soil moisture retrieval algorithms. Change detection in surface characteristics is possible when a pair of single frequency SAR scenes are analysed for both amplitude and phase. The idea is to combine retrieval algorithms based on theoretical surface scattering models with coherence maps calculated from phase information in single look complex (SLC) data. Two radar echoes will be coherent if each of them represents nearly the same interaction with a set of scatterers (Derauw, 1995). Lack of coherence is explained by changes in surface characteristics between the two data takes. In the event of drastic changes in, e.g., the dielectric properties of the surface due to drydown or heavy rainfall, the coherence map should contain information about the amount of change. It is therefore anticipated that the combined use of both amplitude (i.e. backscattering coefficient to be derived from PRI data) and phase (i.e. coherence maps from SLC data) should allow a more accurate determination of soil moisture changes in catchments.

Blöschl et al. (1993) demonstrated that the spatial organization of soil moisture influences hydrology at both the hillslope and catchment scale. They showed that a traditional geostatistical approach to distribute soil moisture spatially underestimates catchment scale runoff compared to a more realistic distribution based on topography. Remote sensing has potential for providing information about the spatial distribution of soil moisture and its link with topography. Simulation studies (e.g. Entekhabi et al., 1994) suggest that these data may be extrapolated to give soil depth profiles of soil moisture.This project aims at using ERS data to test these hypotheses.
An important application of interferometric analysis of SAR data is the generation of digital terrain models (DTM). Although it is recognized that these DTM's are prone to be in error and that these errors may be significant in hydrological applications, they are however likely to be the only reasonable accurate DTM data source for many places in the world. Therefore, it is important to test the use of SAR derived DTM's for hydrological purposes in well documented river catchments. Techniques developed by Walker (1996, in preparation) will be used to asses the magnitude of DTM error, and the overall effect on geomorphic attributes that determine hydrology.

2. Experimental plan and data requirements
2.1. SAR-soil moisture inversion algorithms and interferometric SAR data analysis

Since microwave remote sensors do not measure soil moisture directly, a retrieval algorithm is needed to extract this information from the measured signals which are often contaminated with noise. From a mathematical point of view, this is equivalent to solving an inverse problem closely related to forward modelling. Forward modelling develops a set of mathematical relationships to simulate the instrument's response for a given set of model parameters. In the context of soil moisture remote sensing, these parameters generally include soil properties and the geometry and phenology of the overlying vegetation canopy. To solve the inverse problem, it is crucial to start from a forward modelling procedure which is able to adequately describe the observations. It is also important to know the number of model parameters used to describe the subjects being measured and to know which parameters most sensitively influence the returned signal.

Consider the problem of microwaves impinging upon a layer of vegetation canopy overlying a rough ground surface. The waves penetrate the layer and interact with various parts of the inhomogeneous vegetation canopy and with the top soil matrix, resulting in a series of absorption and scattering reactions. A portion of the scattering waves returns to the radar's receiver and carries within it dielectric information regarding the illuminated vegetation-soil medium. In essence, this backscattering process can be subdivided into three components: (1) a component representing the scattering contribution of the vegetation canopy; (2) a component representing the surface-volume interaction contribution; (3) a component representing the ground backscattering contribution, including the two-way attenuation caused by vegetation.

The problem of wave scattering from a randomly rough ground surface has been studied theoretically using both low- and high-frequency approximations. Among the high-frequency scattering models, the Kirchhoff formulation (KF) is the most commonly used. The basic assumption of this method is that the total scattered field at any point on the surface can be computed as if the incident wave is impinging upon an infinite plane tangent to the point. Analytic solutions have been developed for surfaces with a large standard deviation (s) of surface heights, using the stationary phase approximation in conjunction with the Kirchhoff formulation, and for surfaces with small slopes and small s using a scalar approximation. For a ground surface whose s and correlation length are much smaller than the wavelength, the small perturbation method (SPM), which is a low-frequency solution, can be used to estimate the backscattering contribution. The region of validity of the SPM has been extended to higher values of s using a perturbation expansion of the phase of the surface field. Attempts have also been made to unite the KF and the SPM in order to extend the range of validity. This led to the development of two-scale models. More recently, Fung (1994) has developed a surface scattering model based on the surface field integral equations called the Integral Equation Model (IEM). The IEM reduces to the SPM when the surface is smooth, and to the standard Kirchhoff model when s is much larger than the incident wavelength.

Microwave scattering models for a vegetation canopy can be categorised into two classes: empirical (or phenomenological) models, and physical (or theoretical) models. The empirical models are based on intuitive understanding of the relative importance of various vegetation parameters, then summing up the contributions from each component believed to be important. The physical models are based upon the modelling of the interactions between microwaves and the various scattering elements of a vegetation canopy (Lang et al., 1986). The major difficulties in modelling these interactions are the determination of the canopy geometry and the multiple-scattering pattern. It is common practice to model the vegetation canopy either as a continuous medium with specific dielectric properties, or as a mixture of discrete scatters randomly distributed in an inhomogeneous layer.

For years synthetic aperture radar has been used to produce photograph-like images of terrain features. While complex data (both phase and amplitude) are collected to produce the SAR image, only magnitude information is withheld and the phase information is discarded. Radar interferometry, on the other hand, depends on phase information. Together, SAR interferometry provide additional information to that of a conventional SAR. InSAR (interferometric SAR) can e.g. detect slight changes in scene content. Changes in surface features (e.g. dielectric properties and/or roughness characteristics) can be detected through coherence measurements. Coherence is a measure of the correlation between two signals (Derauw, 1995). Two radar echoes will be coherent if each represents nearly the same interaction with a set of scatterers. If the scene changes between the two takes, the phase will vary and a loss of coherence will occur. The combined use of conventional SAR and InSAR offers new opportunities for the retrieval of geophysical parameters of the Earth's surface. SAR observations of the same area over a very short time interval is required to relate loss of coherence to well defined atmospheric circumstances (e.g. rainfall, strong dry- down due to solar insolation). These conditions are met for the first time for space observation through the ERS tandem mission.

2.2. Ground truth data acquisition

2.2.1 description of test sites

Tarrawarra catchment, near Melbourne (Australia): The Tarrawarra site is located within the square bounded by 145o26' E, 145 o27' E, 37 o39' S, 37 o40' S. The catchment has an area of 10 ha. The catchment elevation is approximately 100m. The maximum relief is 27m and the hillslopes typically have slopes of 11-14%. The main drainage line has a mean slope of 4%. The land is used for dryland grazing of dairy cows and has improved pastures. Tarrawarra has a temperate climate with a mean annual rainfall of 1000mm and a class A pan evaporation of 1200mm. The major soil type is a duplex soil with a loam-clay loam A horizon which has a bleached A2 horizon. The B horizon is a heavy yellow-grey mottled clay. The A horizon is 30- 35cm deep over the majority of the catchment and the B horizon varies between 0.5m and more than 1.4m thick.

Wijlegemse beek catchment, near Gent (Belgium): The Wijlegemse beek catchment is located in the Zwalm catchment and has an area of 250 ha. The Zwalm catchment is situated in East-Flanders, Belgium, and is a tributary of the Scheldt river. The drainage divide of the catchment expands from 50 45'48" to 50 54'16" N latitude and from 3 40'17" to 3 50'15" E longitude. The total drainage area is 114.3km2. The three main soil types are sandy loam, loam, and clay. The depth of the eolic sandy loam to loam cover is estimated to range between 0 and 10 m. The topography of the basin is characterized by rolling hills and mild slopes. The maximal elevation difference in the basin is equal to 150 m. Climatic conditions can be described as humid temperate. The mean yearly rainfall is 775 mm and is distributed almost uniformly over the year. The catchment was a test site during the last EMAC'94 (ESA) campaign and during the SIR-C/X-SAR (NASA) campaign. The catchment is currently a test site for the EV5V-CT94-0446 E.C.-project in the third framework Environment Programme.

2.2.2 ground truth data acquisition

Tarrawarra test site(1) Permanent instrumentation: An automatic weather station has been installed in the catchment and is monitoring: dry bulb temperature, wet bulb temperature, ground surface temperature, soil temperature at 2, 5, 10, 20 and 50 cm, rainfall, global radiation, net radiation, wind speed, and wind direction. Data from this weather station is used to determine rainfall inputs and evaporative fluxes. A flume has also been installed to monitor surface runoff continuously.

(2) Soil moisture monitoring: Soil moisture monitoring at this site is probably the most detailed one undertaken anywhere in the world so far. Soil moisture is being monitored in two ways. Time Domain Reflectometry (TDR) is being used to monitor soil moisture on regular grids within the catchment. This is being done using a Terrain Data Acquisition System (TDAS). TDAS employs an all-terrain vehicle with a position fixing system (GPS) which allow the operator to drive to predetermined sampling locations. It carries four TDR probes which are inserted hydraulically. In this way the mean soil moisture in the top 30cm of the soil profile is being measured. A 10mx20m sampling grid is used across the whole catchment. More detailed measurement can further be made in parts of the catchment using a 2mx2m grid. Secondly, Neutron Moisture Meters are used to provide information on the vertical movement of soil water. This will assist the interpretation of observed changes in the spatial soil moisture pattern. Twenty neutron probe access tubes have been installed. These access tubes were placed in the drainage line, on the midslopes and at or near the drainage divide. For each of the satellite passes, over 500 TDR readings will be taken, along with depth profiles from the neutron moisture meter sites.

(3) Soil characterization: Currently, a significant effort is being made to characterize the hydrologic characteristics of the soils in the catchment. A detailed soil map of the catchment is prepared including information on soil type and the depth of the A horizon. Vertical and lateral hydraulic properties of the soil (A and B horizons) are being measured. Particle size distribution and bulk density are also measured and used to characterize spatial changes in soil properties. Also ground penetrating radar (GPR) is going to be used to assist in describing the spatial characteristics of the soil profile.

(4) Digital elevation model: a detailed (1500 spot elevations accurate to 5 cm) ground based topographic survey has been completed for Tarrawarra.

Wijlegemse beek test site

(1) Permanent instrumentation: An automatic weather station has been installed in the catchment and is monitoring: dry bulb temperature, wet bulb temperature, ground surface temperature, soil temperature at 2, 5, 10, 20 and 50 cm, rainfall, global radiation, net radiation, wind speed, and wind direction. Data from this weather station is used to determine rainfall inputs and evaporative fluxes. A flume has also been installed to monitor surface runoff continuously. A transect of 20 piezometers is installed perpendicular to the main stream of the basin, in order to study the phreatic groundwater table position and fluctuations.

(2) Portable surface flux stations: During intensive field campaigns the surface fluxes of latent and sensible heat can be determined using a portable Bowen ratio station and a portable eddy correlation station.

(3) Soil moisture monitoring: In the vicinity of the automatic weather station a vertical profile consisting of 4 TDR probes is installed to monitor vertical water movement in the top 50 cm of the soil layer. During the time of satellite overpass soil moisture is measured using handheld TDR probes and gravimetric sampling techniques.

(4) Soil characterization: A detailed soil map exists for the catchment (scale 1/20,000). This map contains information on the soil texture, drainage conditions, and profile development. In addition the determination of hydraulic properties is planned in the framework of a research project to be financed by the University of Ghent.

(5) Digital elevation model: a detailed (4x4 m) digital elevation model has been constructed based on the 1/10,000 scale topographic maps available for the site.

2.3. Spatial patterns of soil moisture and geomorphic terrain features

Blöschl and Sivapalan (1995) discuss the nature of spatial variability and hetero- geneity in a review of scale issues in hydrology. Of particular interest in this project is the concept of organization. Organization is similar to regularity or order but tends to relate to a more complex form of regularity. In some cases, spatial organization may reflect adaptive landscape development, while in others it may reflect water routing processes or spatial pattern of precipitation and evapotranspiration. Spatial organization of a variable implies that its variation in space is characterized by the presence of complex spatial relationships. Because of this, traditional geostatistics are not sufficient to fully characterize the spatial patterns. Many geostatistical applications rely upon the intrinsic hypothesis of second order stationarity of the difference between a variable at two different points. Generally, this hypothesis is not met when organization is present. Blöschl et al. (1993) demonstrated the importance of organization of soil moisture patterns at the hillslope and catchment scale. They simulated runoff hydrographs based on organized and random spatial patterns of antecedent soil moisture, hydraulic conductivity and precipitation. While the covariance structure of the organized and random cases was identical, the runoff response was vastly different. Remote sensing obviously has potential for providing the spatial data required to further our understanding of the spatial characteristics of catchments. However there are problems with interpretation of remotely sensed soil moisture data which need to be addressed before it will see routine applications in hydrology. This research proposal aims at resolving some of these technical difficulties.

One of the concepts often applied in catchment hydrology is the wetness or topographic index. Wetness indices have been used to predict the spatial distribution of soil moisture. The effect of this spatial organization upon radar retrieval of soil moisture, possible interaction with vegetation cover, and the ability to identify spatial organization with SAR are important questions for which definitive answers are yet to be developed.

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